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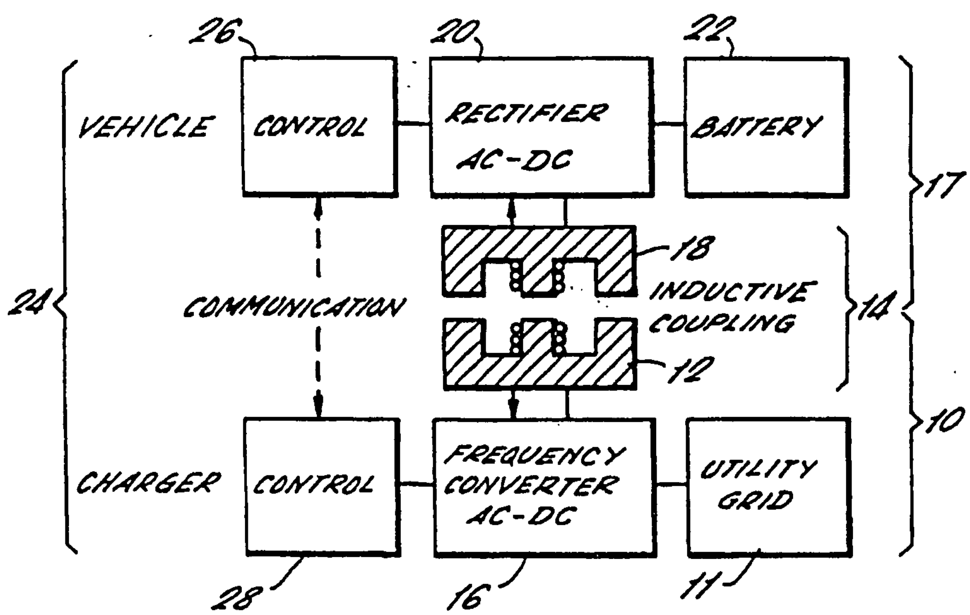

(57) Abstract

This invention relates to a method and system for re–charging the traction battery of an electrically–powered vehicle by inductive coupling of a primary winding connected to a power supply with a secondary winding mounted in the vehicle. The operating frequency of the primary winding is maintained in a selected range which is from a selected resonance frequency of the primary winding to a frequency which is less than a selected resonance frequency of the secondary winding.

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BATTERY CHARGERS

INTRODUCTION

This invention is concerned with a system and method for charging batteries and more specifically for charging traction batteries of electrically-powered vehicles.

BACKGROUND

Traction batteries for electrically-powered vehicles require regular charging and there are essentially two approaches to so doing, namely the conductive approach (requiring a hardwired connection between the battery and the power supply) and the inductive approach, which does not require hardwiring. This invention is concerned with the inductive approach.

Inductive coupling offers a solution where power can be transferred across air gaps, hence eliminating the need to attach the battery physically to terminals for charging of the battery - with its potential attendant hazards for the user. Inductive charging systems for electric vehicles are fundamentally safer than conductive systems and reduce the dependence upon the user by offering the user total automation of the battery charging process. However, in order to offer a totally automated battery charging system, the charge connection does need to be made without any intervention of the user.

Inductive coupling overcomes the safety concerns associated with conventional conductive coupling and, with appropriate control, extra benefits such as automatic charging can be gained. In addition, there are no wear points at the interface resulting in high ease of use, long life expectancy, no moving parts and no possibility of 'arcing' when connecting or

disconnecting. The inherent safety features make inductive charging ideal for public charging stations at which vehicle users can recharge the batteries of their vehicles. An automated system such as is contemplated by the present invention also provides a potential equivalent, in terms of charging traction batteries, to the established fuel station where a user can automatically recharge the battery of a vehicle.

Electric vehicle inductive battery charging systems, or power transfer systems, can be categorized as three distinctly different groups, hand-held systems, automated recharge systems and inductive tracks.

In 1980, a system known as the Inductran system was developed for contactless power transfer to electric vehicles. The system is simply a mains frequency transformer split into two halves with the primary inductor mounted on the floor or hung on a wall. The secondary inductor has to be in contact with the primary inductor in order for the system to operate efficiently however due to the insulated coatings of the two inductors the coupling has an effective air gap of 10mm.

The primary winding of this system is connected directly to the mains network. Both the primary and secondary windings have shunt connected capacitors which compensate for the large magnetizing current. The system exploits the ferro-resonant principle and, by ensuring the laminated iron cores are always magnetically saturated, a stable AC voltage is induced on the secondary side. A rectifier associated with the secondary winding converts the AC power to DC to charge the battery. A power transfer of 3kW of power can be achieved at 80% efficiency. By reducing the air gap the efficiency can be increased due to the reduced leakage flux; however, for a changed air gap the inductor cores have to be redesigned and additional components changed. For the circuit to operate, the air gap has to be maintained at the designed clearance. Direct connection

to the utility grid and operation with saturated cores means the system suffers from poor power factor and harmonic problems.

In a development of the Inductran system, a 400 Hz inductive coupler has been tested based on a pot core design. A conical inductor has been suggested which allows accurate self alignment.

Further developments to provide a completely automated self service electric car have been made in which vehicles are parked in predefined parking lots and will be available to members of the public who have subscribed to the system. These parking lots contain a fully automatic inductive charging station that requires no intervention from the user. One such development uses a high frequency inductive coupler and the primary and secondary inductors are constructed from shallow ferrite pot cores which have a maximum air gap of 8mm while the primary winding is supplied from a resonant inverter. Various resonant converter topologies have been suggested; for a 3kW charger a series resonant inverter is suggested. The primary winding forms the inductive element and the inverter (IGBTs can be connected either in the half or full bridge configuration). The published waveform showed operation above resonance at 25kHz. A parallel inverter circuit using just one switching element has also been devised. It was suggested that this circuit would only be used for low power applications such as electric scooters due to increased losses and electromagnetic interference (EMI) problems caused by non sinusoidal current waveforms.

The secondary winding of the coupling directly connects to the in-vehicle rectifier whose output is filtered to charge the vehicle battery. The system has been developed for automated alignment to a tolerance of 1mm when the maximum power transfer is 3.3kW. There is no compensation on board the vehicle for the effects of

the air gap, and therefore any increase in air gap severely reduces the power transferred and the operating efficiency. Furthermore, this system uses a mechanical alignment system with docking of the vehicle with floor mounted elements which could become damaged.

Another similar development requires the vehicle in question to be correctly positioned on a centering control linking a sensor of the vehicle to the inductor. The power is reported to be 1.5kW at an air gap of 40mm, and the maximum air gap is specified as 50mm at which spacing however power transfer is reported to fall to 1kW. The system is said to operate from a 380V AC supply and to have a DC output of 60V.

These prior art systems offer the possibility of some automation. Air gaps are quoted as 8-10mm with the insulated casing of the two inductors in contact. Solutions have been suggested which allow the primary inductor to be raised off the ground and placed in a parking bay and the vehicle has to be positioned very accurately by the driver above the inductor. The amount of power transfer considerably reduces with any misalignment.

In a further development by General Motors and Hughes Power Control Systems, a flat plate-shaped hand-holdable inductive coupling 'paddle' is connected to a charging station and is inserted by hand into a purpose designed port in the vehicle. The primary inductor is provided in the paddle, and the port on the front of the vehicle is the location for the secondary inductor. The unit is connected to the distribution system via an EMI filter. Harmonic distortion on the input current is reported to be typically less than 3%. Built into each hand-held paddle and vehicle charge port is a transmitter and receiver enabling communications at 915 MHZ between the car and charger. Units rated at 3kW to 25kW are available while models up to 100kW are under development. This proposed system does require special

adaptation of the vehicle to accommodate the port and the secondary inductor and provision of special paddle stations which can be subject to damage or mis-use.

This development has very close coupling between the primary and secondary inductors. The air gaps are very small and the system is very efficient. However, the structure is not suitable for complete automation since the mechanical tolerances are similar to those of direct connection plugs and have been designed as a safer alternative to direct connection plugs.

In the continued development of electric vehicles, an unique roadway powered electric vehicle (RPEV) system has been proposed and constructed that receives electric power by inductive coupling from an inductor buried beneath the road surface. An analytical model of the system that transfers power from the road to the vehicle battery and vehicle motor has been developed and a primary inductor of 11,000 feet length was constructed, split into segments of 250 to 500 feet. A secondary inductor was mounted beneath a vehicle and its dimensions were 13 feet long and three feet wide. The primary inductor was supplied with 400Hz single phase AC from a 230kVA rectifier inverter system. The primary winding had 8 aluminum cables connected in parallel to form a one turn coil carrying about 1,000A at 400Hz. The pick-up inductor has 18 copper cables which are connected as two turns for the experimental system.

The 75mm air gap between the primary track and the secondary pick-up and the long uncoupled portion of the primary track meant that only a small portion of the flux generated by the track current actually coupled with the secondary winding. The result is a low magnetizing inductance and a large magnetizing current. To compensate, a variable capacitor bank was connected across the terminals of the pick-up winding to form a resonant circuit. The primary current operated at the resonant frequency of the pick-up (400Hz) which enabled

the capacitor bank to compensate for the magnetizing inductance and thus maximum power was transferred. Adjustment of changes the resonant frequency of the system, which, because the operating frequency was fixed led to a change in secondary terminal voltage. On board computer control tuned the system in response to load current demands by automatically adjusting the tuning capacitor. This was achieved by switching in and out different values of capacitor. It has been proposed to combine the RPEV system with automatic lateral and longitudinal control to offer a completely automated vehicle.

The RPEV system is designed to continually drive the traction motor along inductive tracks. The RPEV primary inductor is buried beneath the road surface allowing the system to be used on normal roadways and overcomes problems of low coupling coefficients by utilizing resonant systems but the system is not suitable for automated opportunity charging. The system is considered to be inefficient and is said to suffer from a considerable reduction in power transfer with any misalignment. The RPEV system is far too heavy with a mass of 850kg while its long track adds considerably to capital and installation costs.

As will be understood from the discussion of the prior art, none of the previously available systems for inductive power transfer is completely suitable for automatically charging truly mobile electric vehicles and would not satisfy the requirements of safety, automation and widespread availability that a system and method according to the present invention would provide.

European Patent Application 0558316 discloses an inductive loop system for applying power, principally in the medical/surgical environment, in which primary and secondary circuits are operated at the same resonant frequency.

International Patent Application WO 93/23908

discloses a system for coupling power to an electrically-powered moving vehicle in which a plurality of primary circuits are serially coupled to a secondary circuit provided on the vehicle with the resonant frequency of both primary and secondary circuits maintained at or close to a consistent frequency.

International Patent Application WO 94/28560 also discloses a power coupling system, suitable for use in potentially hazardous environments, in which the secondary winding is connected in a resonant circuit and the AC power supply coupled to the primary circuit is tuned to the resonant frequency of the resonant circuit.

U.S. Patent 5428521 further discloses power supply apparatus which operates with the power frequency applied to the primary coil being equal to the resonant frequency of the secondary coil.

U.S. Patent 5654621 discloses a system for charging a vehicle battery in which a movable primary coil is set in a suitable well or pit in the ground for a vehicle to be aligned therewith can be manoeuvred so that a secondary coil of a battery charging circuit carried by the vehicle can be aligned with the primary coil in inductive relationship, the resonant frequency of each of the primary and secondary circuits being at the same frequency.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and system which will enhance the efficiency of inductive power transfer between power sources and the batteries of electric vehicles so that such batteries can be automatically charged with minimal or no user intervention.

The invention is specifically concerned with a system comprising a primary circuit and a secondary circuit which can be inductively coupled by the inductive coils or windings of the two circuits and in

which the secondary circuit of the system is mounted in the vehicle and is connected to the battery of the vehicle, while the primary circuit is coupled to a power source, such as a mains power supply, at a location at which the secondary circuit can be brought into operable proximity to the primary circuit to be inductively coupled thereto for charging of the battery. Such a system is hereinafter referred to as "a system as defined herein".

The present invention provides a method of charging the traction battery of an electrically-powered vehicle, using a system as defined herein, the method comprising the steps of inductively coupling the primary and secondary inductor circuits of the system, and characterised by maintaining the operating frequency of the primary circuit in a selected range from a selected resonance frequency of the primary circuit to a frequency which is less than a selected resonance frequency of the secondary.

Carrying out a method according to the invention allows compensation for any loss of power to the battery due to imperfect alignment of the windings of the two primary and secondary circuits.

In carrying out a method according to the invention, it is preferred that maintaining the operating frequency of the primary circuit in said range is achieved by providing tunable capacitor means in the primary and secondary circuits; establishing the resonant frequency of the secondary circuit when the primary and secondary windings of the system are optimally inductively coupled; adjusting the capacitance to produce resonance in the primary circuit at a frequency which is less than that of the resonant frequency of the secondary circuit, and generating frequency in the primary circuit which is in said range.

Preferably, maintaining of the operating frequency of the primary circuit in said range is effected by

remote control. Remote control may be effected by electromagnetic communication between the vehicle and frequency control receiver means connected to the primary circuit.

In carrying out a method according to the present invention it is preferred that the primary circuit is located at ground level. "Ground level" means on the ground, partially embedded in the ground or located in a position in which the coil or winding of the primary circuit is mounted just below the surface of any hard standing provided for the vehicle in question, such as a roadway, driveway, battery charging bay or garage forecourt.

The present invention further comprises a system so defined herein for establishing and maintaining the operating frequency of the primary circuit in a range from a resonance frequency of the primary circuit to a frequency which is less than a resonance frequency of the secondary circuit. The system may also comprise control means connected to the primary circuit for controlling the operating frequency of the primary circuit, transmitter means associated with the secondary circuit and receiver means connected to the control means for receiving transmissions from the transmitter means to control the operating frequency of the primary circuit.

The present invention further provides a method of compensating for non-optimal alignment of the primary and secondary circuits of an electromagnetically inductively coupled system comprising both circuits, each circuit comprising tunable capacitor means, the method comprising the steps of supplying electrical power via the primary circuit to the secondary circuit to induce current flow in the secondary circuit, and controlling and adjusting the operating frequency of the primary circuit to maintain the value of the operating frequency within a range from a resonance frequency of

the primary circuit to a frequency which is less than a resonance frequency of the secondary circuit.

The present invention further provides means for compensating for non-optimal alignment of the primary and secondary circuits of an electromagnetic inductor system comprising both circuits when brought into mutually inductive relationship, the primary and secondary circuits each comprising tuning capacitor means, the compensating means comprising means for controlling the frequency of the primary circuit to maintain the value of that operating frequency in a range from a resonance frequency of the primary circuit to a frequency which is less than a resonance frequency of the secondary circuit.

DESCRIPTION OF THE DRAWINGS

There now follows a description which is to be read with reference to the accompanying drawings of methods, systems and means which have been selected to illustrate the invention by way of example.

In the accompanying drawings:

Figure 1 is a block diagram of a system according to the present invention which provides easy and efficient electric vehicle (EV) battery recharging with no tactile intervention from the user;

Figure 1A is a flow diagram illustrating the steps required to re-charge a battery using a system according to the present invention;

Figure 2 is a schematic cross-section of an inductor design suitable for use in a system according to the present invention;

Figure 3 is a circuit diagram of a power circuit suitable for use in a system according to the present invention;

Figure 4 is an analytical circuit diagram corresponding to the circuit of Figure 3;

Figures 4(a) and 4(b) illustrate equivalent

circuits to Figure 3 in parallel resonant and series resonant configuration for ac analysis;

Figure 5 is a graph showing frequency response of system voltages in an example of a system according to the present invention;

Figure 6 is a graph of frequency response against system currents in an example of a system according to the present invention;

Figure 7 is a graph showing the effects of secondary compensated and uncompensated coupling on voltage over a range of frequencies in a system according to the present invention which includes an ideal sinusoidal voltage source;

Figure 8 is a graph showing a comparison between an aligned and a misaligned coupling with a constant voltage supply in a system according to the present invention;

Figure 9 is a graph indicating the results of experiments carried out with a system according to the present invention showing the relationship of normalised voltage in the secondary circuit of the system to frequency;

Figure 10 is a graph illustrating the relationship of the current displacement angle with frequency for both the primary and secondary currents in a system according to the present invention.

SPECIFIC DESCRIPTION

The illustrated embodiment is specifically concerned with the transfer of power from the utility power grid, or equivalent source of power such as a generator, to a vehicle traction battery across an inductive coupling. The inductive coupling typically has a large air gap to allow the mounting of the secondary inductor on the underside of a vehicle while the primary inductor can be fitted flush with the road surface. To allow for vehicle positioning error a

system according to the invention is designed to be tolerant of some physical misalignment whilst maintaining an acceptable rate of power transfer and operating efficiency.

Referring to Figure 1, the electric vehicle traction battery charging system according to the invention, which is shown diagrammatically therein, comprises a primary circuit 10, which includes a three-phase rectified mains voltage supply 11, connected to a primary winding or inductor 12 of an inductive coupling generally indicated at 14 by a resonant inverter 16, and a secondary circuit 17 comprising the secondary winding 18 of the inductive coupling 14 which is connected to a vehicle battery 22 by an ac-dc rectifier 20. The secondary circuit is housed in the vehicle.

The primary inductor 12 is intended to be housed at ground level, e.g. in a road surface, driveway or any location that can provide hard standing or support for an electric vehicle, and the secondary winding 18 is provided on the underside of the vehicle so that the vehicle can be driven over the location of the primary inductor 12 and the secondary winding or inductor inductively coupled to the primary inductor for charging of the battery. When correctly aligned, current is induced in the secondary inductor and the battery charged, the ac supply from the inductive coupling being converted to dc to charge the battery 22.

As is hereinafter described, the system according to the present invention provides means for compensating for misalignment of the secondary winding with the primary winding when the vehicle is positioned over the primary winding and such means includes means for controlling adjustment of parameters of the circuit supplying power to the vehicle battery. The control means comprises a transmitter/receiver arrangement generally indicated at 24, one transmitter/receiver means 26 of which is mounted in the vehicle and a second

transmitter/receiver means 28 of which is connected to the power supply circuit.

The procedure for charging a traction battery of a vehicle is indicated in Figure 1A. On determining from the vehicle instrumentation that its traction battery requires re-charging, the driver will move the vehicle to a location at which charging facilities will be provided. The vehicle is positioned so that its secondary inductor is positioned as accurately as can be determined by eye over the primary inductor.

The system may be activated by the driver/owner of the vehicle by use of a swipe card, credit card or other means of identification or by an authorised operator, and the secondary winding will then be coupled inductively to the primary inductor and charging of the traction battery of the vehicle will commence.

The primary circuit 10 comprises associated monitoring means to determine that the system is charging the battery efficiently and includes means, hereinafter described, for adjusting the power supply, and in particular the frequency thereof, from the primary circuit to ensure maximum efficiency of power supply, according to the physical disposition of the vehicle and its secondary inductor relative to the primary inductor.

Charging of the traction battery terminates when the monitoring means indicates that the battery is fully charged.

In an alternative and fully automated arrangement, means may be provided on board the vehicle for providing the same information to the driver of the vehicle and for permitting the driver to adjust the power supply from within the vehicle so that the charging of the traction battery can take place without the driver leaving the vehicle.

The vehicle can be fitted with sensor means which cooperate with means provided at the site of the primary

inductor to permit signals to be generated to indicate to the driver of the vehicle that an optimum position has been adopted for charging to take place.

As will be described below, the means 26 has a number of basic functions which are to monitor the output of the primary circuit 10 via the transmitter/receiver means 28 and to provide the user of the vehicle with an indication as to the efficiency with which the vehicle battery is being charged so that the user can transmit an adjusting signal to the primary circuit 10 to cause appropriate adjustment of the output of the primary circuit, while the transmitter/receiver means element 28 has the function of monitoring the primary circuit output, transmitting information relating to that output to the means 26 and responding to signals received from the means 28 to adjust the output of the primary circuit 10. Alternatively processor means can be provided on board the vehicle to effect the adjustment, namely by transmitting instructions to the primary circuit to make adjustments to the power supply as required, to maximise the efficiency of charging the battery.

Figure 2 is a cross-section of the primary and secondary inductors 12 and 18 which are provided by two ferrite cores. The facing portions of the ferrite cores are each of an area such as to provide large opposing areas 30 and 32, having the effect of reducing the magnetic reluctance of the air gap and providing for misalignment of the cores. The air gap was chosen to be 75mm to allow the primary inductor to be buried beneath the road surface.

A gap of 75mm is suitable for movement over level ground but may not provide sufficient clearance for use of electrically driven vehicles over less even ground such as country roads or tracks. To accommodate such unevenness, means may also be provided for raising and lowering the secondary inductor so that, when it is

desired to recharge a battery, the secondary inductor can be lowered to a position in which the optimum gap can exist between it and a primary inductor set in, say, a road surface; the secondary inductor can then be raised to a retracted position for normal travel of the vehicle. Such means may be manually, electrically, hydraulically or pneumatically powered.

The power circuit of Figure 2 is shown in more detail in Figure 3, where the primary and secondary inductors 12 and 18 of the coupling device consist of loosely coupled inductor windings LS1 and LS2. The frequency converter 16 of Figure 1 comprises a 3-phase utility grid rectifier circuit 34 connected to an inverter 36. The inverter has a resonant tank 37 formed by the inductive coupling 14, a capacitor Cs series with the winding LS1 and a capacitor Cp in parallel with the winding LS2 respectively. By placing the parallel capacitor Cp on the secondary side of the inductive coupling 14, the leakage reactance of both the primary and secondary inductors 12 and 18 can be utilised in the circuit. The capacitance of the secondary inductor 18 is absorbed into Cp. The equivalent series resistance of both capacitors must be low due to the large circulating currents. The reactance of capacitor Cp is chosen to be lower than the input impedance of the rectifier which results in the output voltage of the inverter being approximately sinusoidal and the inverter acts as a sinusoidal voltage source.

The inverter 36 consists of four switches (S1 to S4) with anti-parallel diodes (D1 to D4 respectively) associated with the switches. Each switch D1-D4 can conduct a positive or negative current. The switching pairs are alternatively turned on and off at the switching frequency with a duty cycle of 50%. The switch arrangement of the inverter 36 applies a square wave or voltage to the resonant tank 37. Due to the

filtering action of the resonant circuit, an approximate sine wave current flows through the primary inductor LS1. High frequency power is rectified on-board the vehicle by the ac-dc rectifier 20 which comprises an array of four fast recovery diodes DR1 to DR4. The dc charging output from the rectifier 20 to the battery 22 is filtered by an inductor Lf.

Figures 4(a) and 4(b) show the circuit of Figure 3 in parallel resonant and series resonant configurations suitable for ac analysis. V_{IN} represents the fundamental input voltage in both circuits, which is applied to the resonant network, while R_V represents the inverter conducting resistance which causes the average conduction loss in the conducting IGBT pair.

C_P is the capacitance of the primary capacitor and R_{CP} represents the equivalent series resistance thereof while R_P and R_S represent the ac resistance of the primary and secondary windings and L_1 and L_2 represent the leakage inductance thereof respectively. C_S is the capacitance of the secondary capacitor and R_{CS}, and L_M is the magnetising mutual inductance of the coupling 14. R_D represents the combined resistance of the output filter inductor and the bridge rectifier and can be estimated from the equation

$$R_D = 2.(V_{FD}/I_D) + R_{LF}$$

Where V_{FD} = rectifier diode forward voltage
I_D = average diode current
R_{LF} = output filter inductor resistance.

The resonant network has the effect of filtering the higher order harmonic voltages so that essentially a sine wave appears at the input to the resonant circuit.

The value of C_S is selected to yield an optimised operating state. It is desirable to minimise

circulating currents in both the primary and secondary circuits and to maintain device terminal voltages at acceptable levels.

AC analysis was performed with the circuit of Figure 4, and Figure 5 shows the system responses to change in voltage as a function of frequency for a perfectly aligned coupling while Figure 6 shows the system currents as a function of frequency, also for a perfectly aligned coupling. From this analysis, it was found that, by selecting a switching frequency higher than the resonant frequency (7kHz nominally), the operation of the circuit is optimised and the system operates with high efficiency, and that adjustment could be made to compensate for core misalignment by adjusting the switching frequency.

In attempting to register the secondary inductor 18 mounted under a vehicle with a ground-based primary inductor 12, there is the distinct possibility that the two inductors will not be accurately aligned to maximise the inductive coupling between the inductors. This is due to the fact that the occupier of a vehicle cannot accurately gauge (to within two or three centimetres) the position of the secondary inductor relative to the primary as these are both beneath the vehicle and the secondary inductor is too close to the ground to permit viewing of its relative position.

With an air gap between the primary and secondary inductors of a constant 75mm, then the frequency response of the circuit was examined and Figure 7 shows the effects of a secondary compensated and uncompensated coupling, in which the primary inductor is supplied from an ideal sinusoidal voltage source, and the primary and secondary inductors are perfectly aligned.

Figure 8 shows a comparison between aligned and misaligned couplings where the supply voltage V_{IN} is constant. The vertical dotted lines represent the operating frequencies required to maintain a constant

output under different alignment conditions.

The trace identified as V2′ in Figure 8 represents the coupling secondary terminal voltage. V2′ is proportional to the amount of power transferred across the coupling. It can be seen that, for a fixed operating frequency, the amount of power transferred will change as the device misaligns. We have found that compensation for this change in power transfer can be achieved through variation in the switching frequency of the inverter and, to achieve this, a series parallel arrangement of correctly chosen tuning capacitors is necessary.

Control of the switching frequency requires that upper and lower operating frequencies need to be established to define an operating frequency band. When the system is turned on for the purpose of charging a battery, the highest frequency is selected and then the frequency is reduced until the desired output or lower frequency limit is encountered. The frequency limits are set according to the rating and values of the chosen circuit components. Classical impedance analysis techniques, such as those described above with reference to Figure 4, were used to analyse the steady state operation of the circuit at 7kHz and it was found, using steady state analysis that the efficiency was 93% with the main power loss being in the inductor windings and inverter bridge.

The main factor to be overcome in increasing the air gap between the primary and secondary inductors of an inductive coupling is the primary and secondary leakage reactance both of which increase slightly with frequency. To overcome the problem of a large air gap it, has been proposed to compensate for the inductive leakage reactance with a capacitive reactance. A capacitor can be introduced across the secondary winding. Figure 8 shows the effect of capacitor compensation with the coupling supplying a resistive

load. The circuit values are summarised in Table 2 below. For simplicity RCS is assumed to be frequency independent.

PARAMETER	VALUE
Compensating capacitance (C_s)	3μF
Compensating capacitor ESR (R_{cs})	5mΩ
Primary winding leakage inductance (L_1)	120.9μH
Secondary winding leakage inductance (L_2)	120.9μH
Magnetising inductance (L_m)	158.6μH
AC load resistance	10Ω
Coupling air gap (Z)	75mm
Coupling alignment	X=0mm, Y=0

Examination of Figure 8 shows that the capacitor compensation causes the secondary winding induced voltage (e) and secondary terminal voltage (V2) to rise with frequency until peaking higher than the uncompensated no-load or loaded values. Both e and V2 then decay rapidly. There will be a circulating current between the secondary winding and the capacitor and consequently the secondary current (I2) will no longer be equal to the output current (I3). The frequency and amplitude of the peak secondary voltage is dependent upon the resonant frequency and Quality factor (QL) of the circuit on the secondary side of the coupling.

Since the load (R_{pr}) is resistive, the peak power transfer will occur when V2 is at a maximum. The peak in secondary voltage (V2) occurs because the circuit has become resonant. Examining the secondary side of the coupling the undamped natural resonant frequency (f_0) is given by the following equation:

$$f_0 = \frac{1}{2\pi\sqrt{(L_2 C_s)}}$$

Under load the peak voltage (V2) with respect to the secondary induced voltage (e) occurs at a frequency lower than the resonant frequency given by,

$$f_{pk} = f_0 \sqrt{(1 - 2k^2)}$$

At this frequency, the peak voltage is given by

$$V2_{pk} = \frac{1}{2k.\sqrt{(1 - k^2)}}$$

where k is the damping factor of the loaded circuit, given by,

$$k = \frac{1}{2Q_L}$$

where Q_L is the loaded quality factor of the coupling secondary side. It is the ratio of the reactive energy to the real energy within the circuit and is given by,

$$Q_L = 2\pi f0C_sRpr$$

Figure 9 shows the relation between f_0, f_{pk}, and V2, while the loaded resonant frequency of the secondary side, denoted by f_d, is shown in Figure 10, in both

cases as a simulated result for perfect alignment. The actual peak in the secondary voltage occurs at a lower frequency than either f_0, $f(V2/e)_{pk}$ or f_d due to the frequency response of e. Maximum power transferred across the coupling occurs at the peak of the secondary voltage ($f(V2/V1)_{pk}$). At this frequency it can be seen that the phase angle of the primary current is at its minimum although still inductive.

We have found by experiment that, for optimum efficiency of vehicle charging, the operating frequency of the primary circuit is in a range from a resonance frequency of the primary circuit to a frequency which is less than the resonance frequency (f_o) of the secondary circuit.

In the above example, the loaded secondary side quality factor (Q_L) was 1.6. Q_L needs to be chosen carefully in order to achieve the most economical power transfer. Q_L will change as a result of changes in either C_s, L_2 or R_{pr}. The secondary leakage reactance L_2 and the induced voltage (e) will vary according to device geometry, number of secondary turns (N_2) or device misalignment. The load RL will not vary significantly over the operating cycle of the charger. The secondary side tuning capacitor Cs needs to be selected to provide the appropriate value of Q_L over the alignment range of the particular device. If Q_L is too large then maximum power transferred will be increased at the expense of a loss in efficiency. There will be a larger circulating current between the secondary winding and the tuning capacitor. Copper losses from the windings will be higher and a suitably higher rated cable will be required. If Q_L is smaller then the circuit will become over damped and cease to be resonant. The result will be a fall in the amount of

power transferred. As a rule of thumb, the value of the capacitance C_s of the capacitor Cs should be chosen to give a reactance at the required operating frequency equal to the resistance of the load. This will ensure Q_L is not too large. It has been found that lowering the Q_L to between 1 and 2 allows compatibility with the traction battery load and higher efficiency.

CLAIMS

1. A method of charging the battery of an electrically-powered vehicle, using a system as defined herein, the method comprising the steps of

inductively coupling the primary and secondary inductor circuits of the system, and characterised by

maintaining the operating frequency of the primary circuit in a selected range from a resonance frequency of the primary circuit to a frequency which is less than a resonance frequency of the secondary circuit.

2. A method according to claim 1 wherein maintaining the operating frequency of the primary circuit in said range is achieved by

providing tunable capacitor means in the primary and secondary circuits;

establishing the resonant frequency of the secondary circuit when the primary and secondary windings of the system are optimally inductively coupled;

adjusting the capacitance to produce resonance in the primary circuit at a frequency which is less than that of the resonant frequency of the secondary circuit, and

generating frequency in the primary circuit which is in the range from said frequency of the primary circuit to a frequency which is less than the resonant frequency of the secondary circuit.

3. A method according to either one of claims 1 and 2 wherein maintaining of the operating frequency of the primary circuit in a range from a selected resonance frequency of the primary circuit to a selected resonance

frequency of the secondary circuit is effected by remote control.

4. A method according to claim 2 wherein remote control is effected by electromagnetic communication between the vehicle and frequency control receiver means connected to the primary circuit.

5. A method according to any one of the preceding claims wherein the primary circuit is located at ground level.

6. A system as defined herein and further comprising means for establishing and maintaining the operating frequency of the primary circuit in a range from a selected resonance frequency of the primary circuit to a frequency which is less than a resonance frequency of the secondary circuit.

7. A system according to 6 wherein the means for establishing and maintaining the operating frequency of the primary circuit in said range comprises tunable capacitor means in the primary and secondary circuits.

8. A system according to either one of claims 6 and 7 and comprising control means connected to the primary circuit for controlling the operating frequency of the primary circuit, receiver/transmitter means associated with the secondary circuit and receiver/transmitter means connected to the control means for receiving and transmitting information and data to control the operating frequency of the primary circuit.

9. A method of compensating for non-optimal alignment

of the primary and secondary circuits of an electromagnetically inductively coupled system comprising both circuits, each circuit comprising tunable capacitor means, the method comprising the steps of supplying electrical power via the primary circuit to the secondary circuit to induce current flow in the secondary circuit, and controlling and adjusting the operating frequency of the primary circuit to maintain the value of the operating frequency within a range from a resonance frequency of the primary circuit to a frequency which is less than a resonance frequency of the secondary circuit.

10. Means for compensating for non-optimal alignment of the primary and secondary circuits of an electromagnetic inductor system comprising both circuits when brought into mutually inductive relationship, the primary and secondary circuits each comprising tuning capacitor means, the compensating means comprising means for controlling the frequency of the primary circuit to maintain the value of that operating frequency in a range from a resonance frequency of the primary circuit to a frequency which is less than a resonance frequency of the secondary circuit.

FIG. 1.

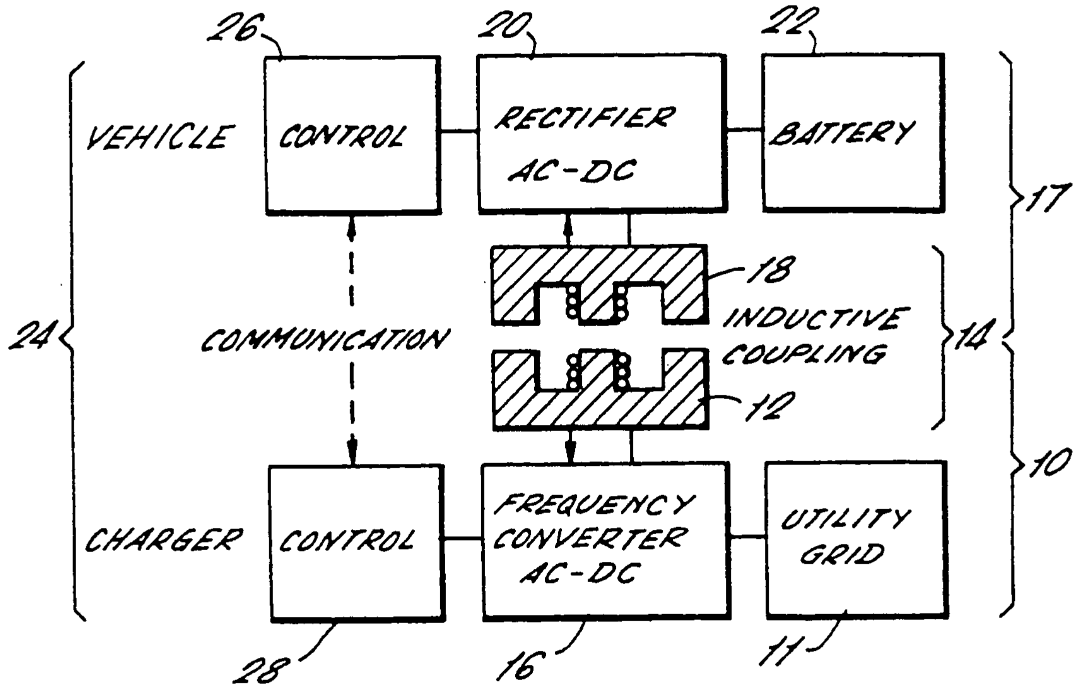

26
20
22
VEHICLE
CONTROL
RECTIFIER
AC-DC
BATTERY
17
18
INDUCTIVE
COUPLING
14
24
COMMUNICATION
12
10
CHARGER
CONTROL
FREQUENCY
CONVERTER
AC-DC
UTILITY
GRID
28
16
11

FIG. 2.

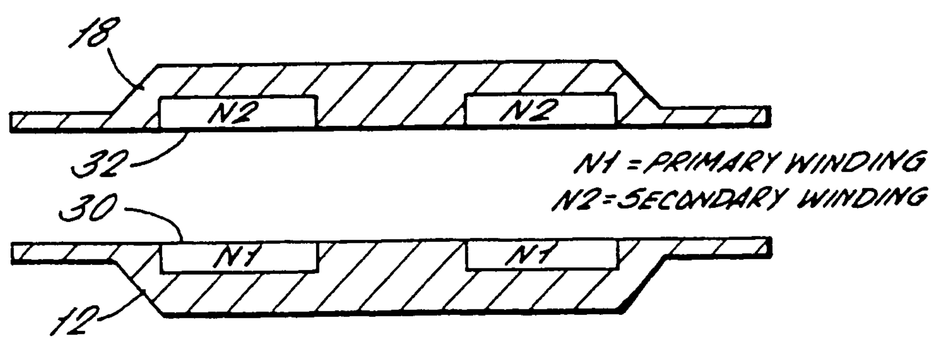
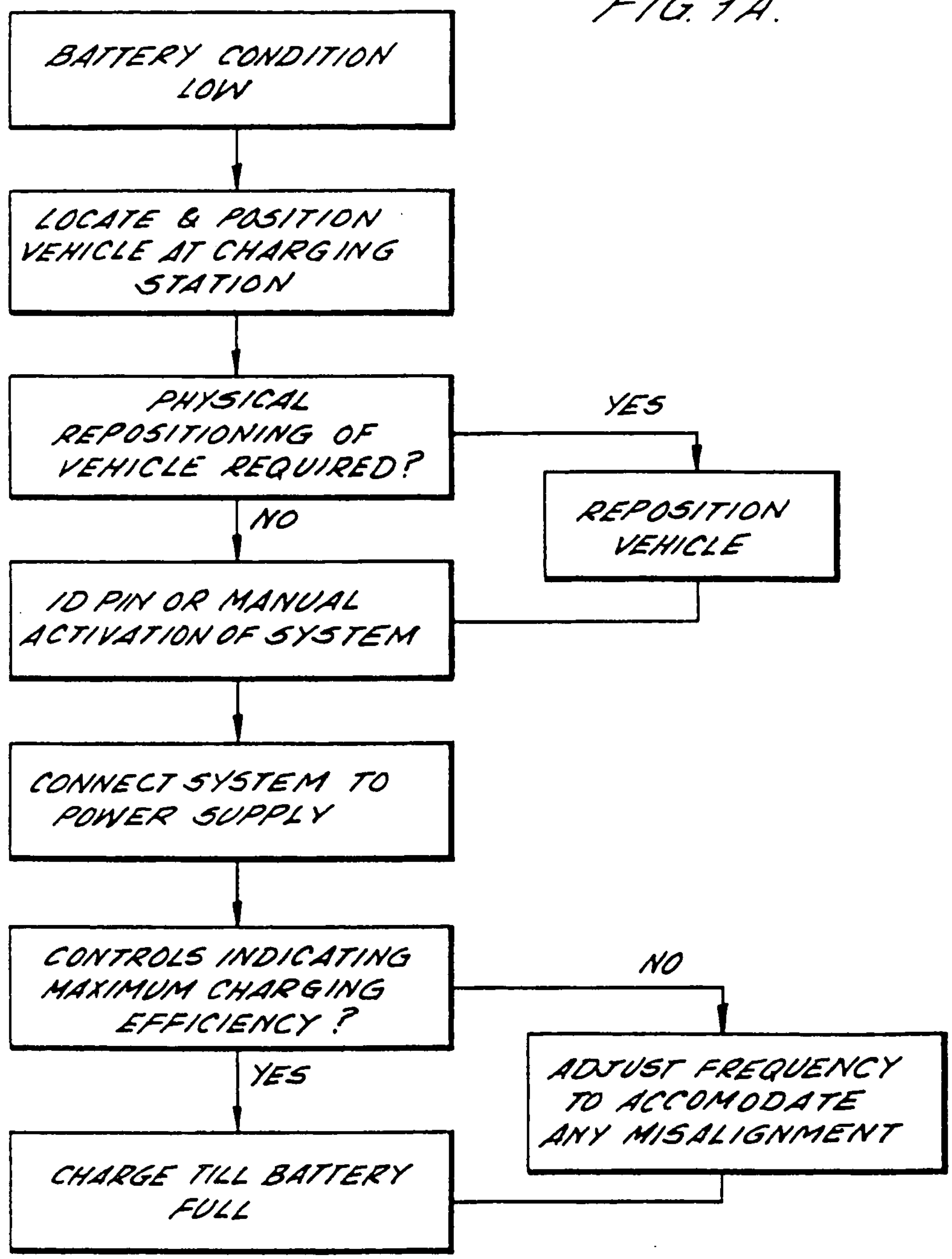

18
N2
N2
32
N1 = PRIMARY WINDING
N2 = SECONDARY WINDING
30
N1
N1
12

FIG. 1A.


BATTERY CONDITION LOW
LOCATE & POSITION VEHICLE AT CHARGING STATION
PHYSICAL REPOSITIONING OF VEHICLE REQUIRED?
YES
REPOSITION VEHICLE
NO
ID PIN OR MANUAL ACTIVATION OF SYSTEM
CONNECT SYSTEM TO POWER SUPPLY
CONTROLS INDICATING MAXIMUM CHARGING EFFICIENCY ?
NO
ADJUST FREQUENCY TO ACCOMODATE ANY MISALIGNMENT
YES
CHARGE TILL BATTERY FULL

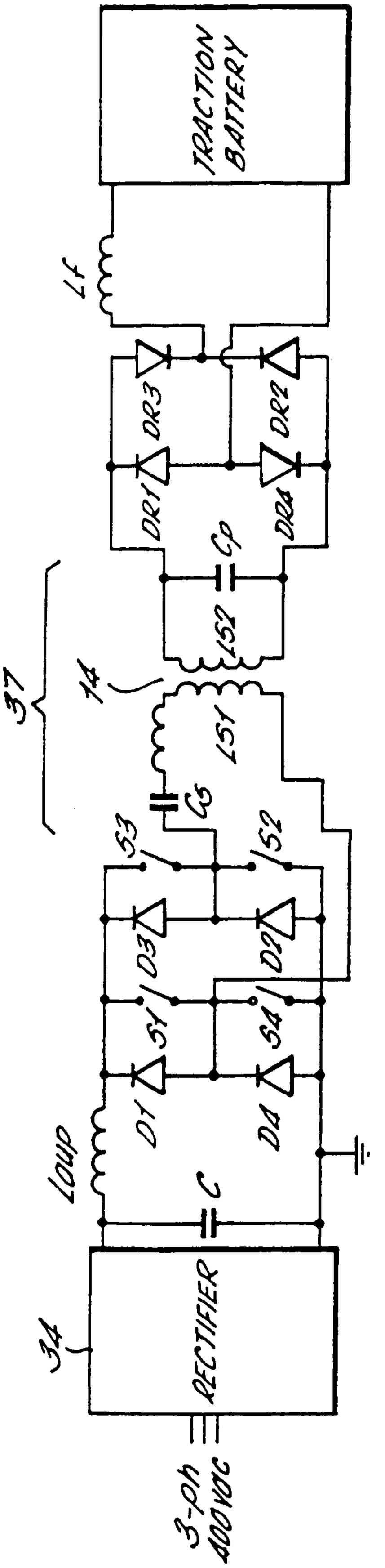

TRACTION BATTERY
Lf
DR3
DR2
DR1
DR4
Cp
LS2
14
37
LS1
Cs
S3
S2
S1
D3
S4
D2
D1
D4
Loup
C
34
RECTIFIER
3-ph 400VAC

FIG. 3.

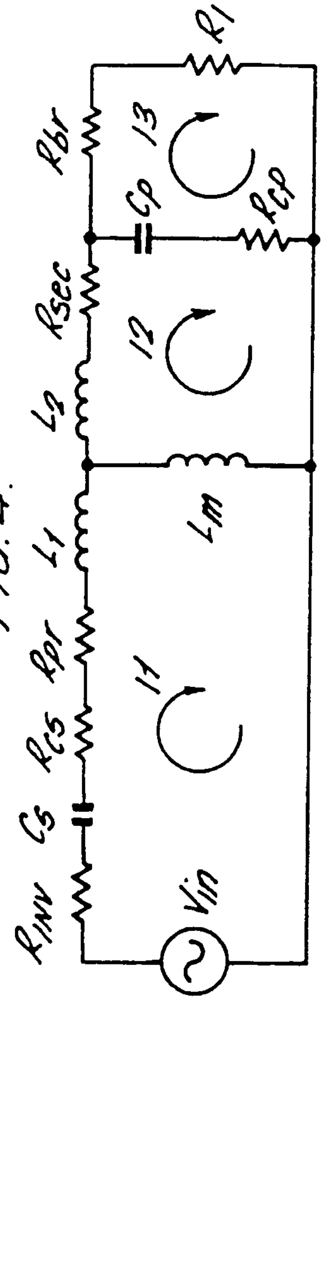

RINV
Cs
Rcs
Rpr
L1
L2
Rsec
Cp
Rbr
Rl
Rcp
Lm
Vin
I1
I2
I3

FIG. 4.

FIG. 4(a) PARALLEL RESONANT INVERTER

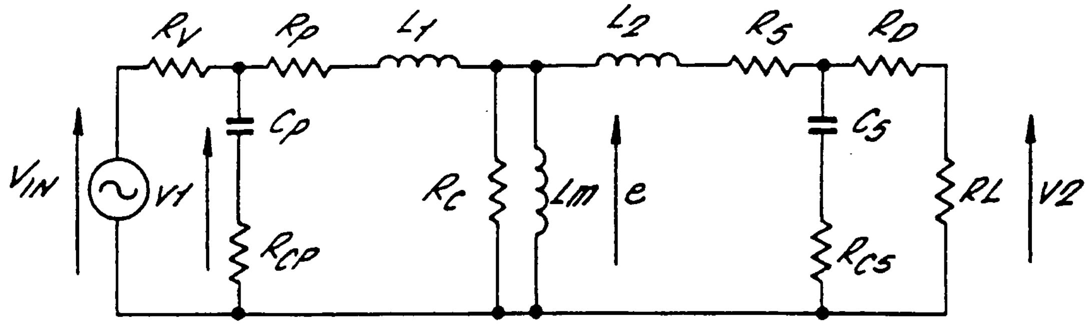


FIG. 4(b) SERIES RESONANT INVERTER

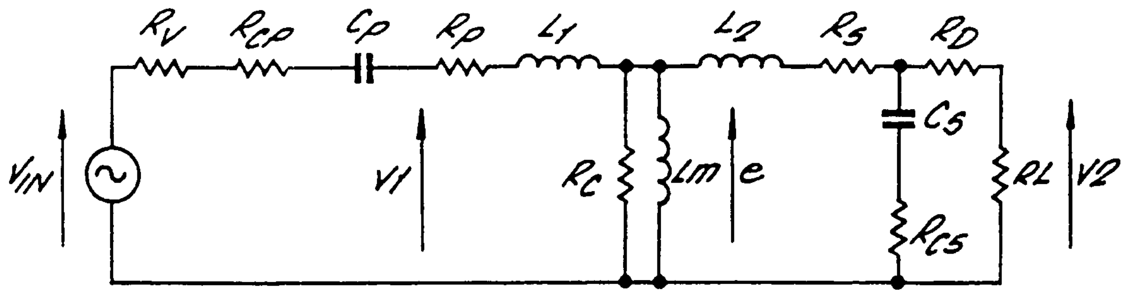


FIG. 5. FREQUENCY RESPONSE OF SYSTEM VOLTAGES.

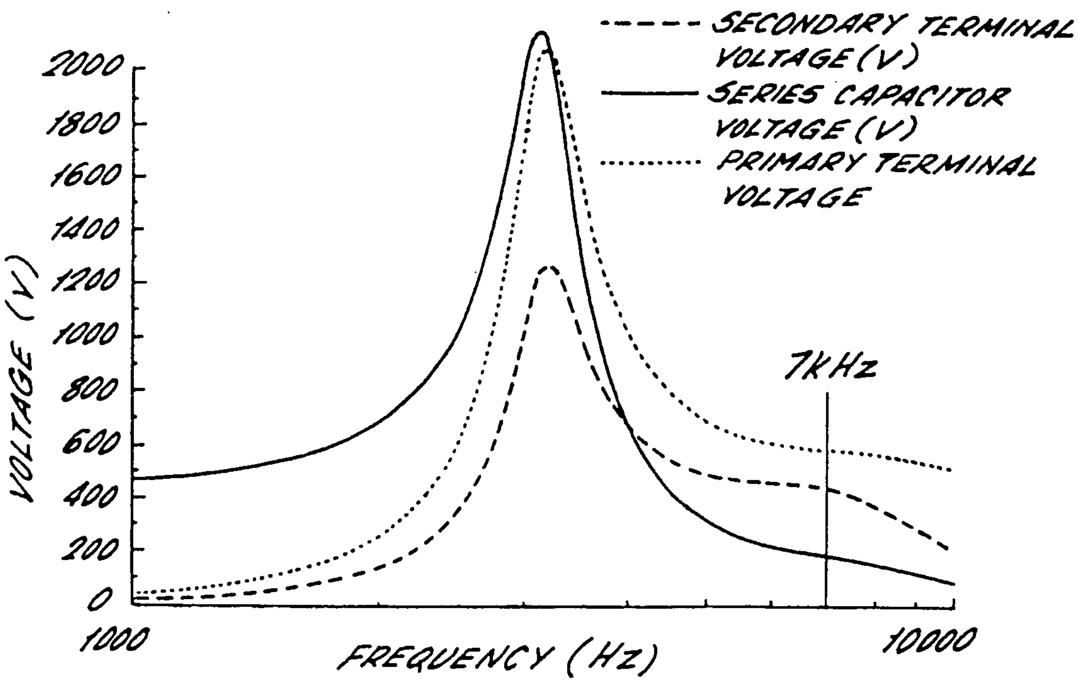
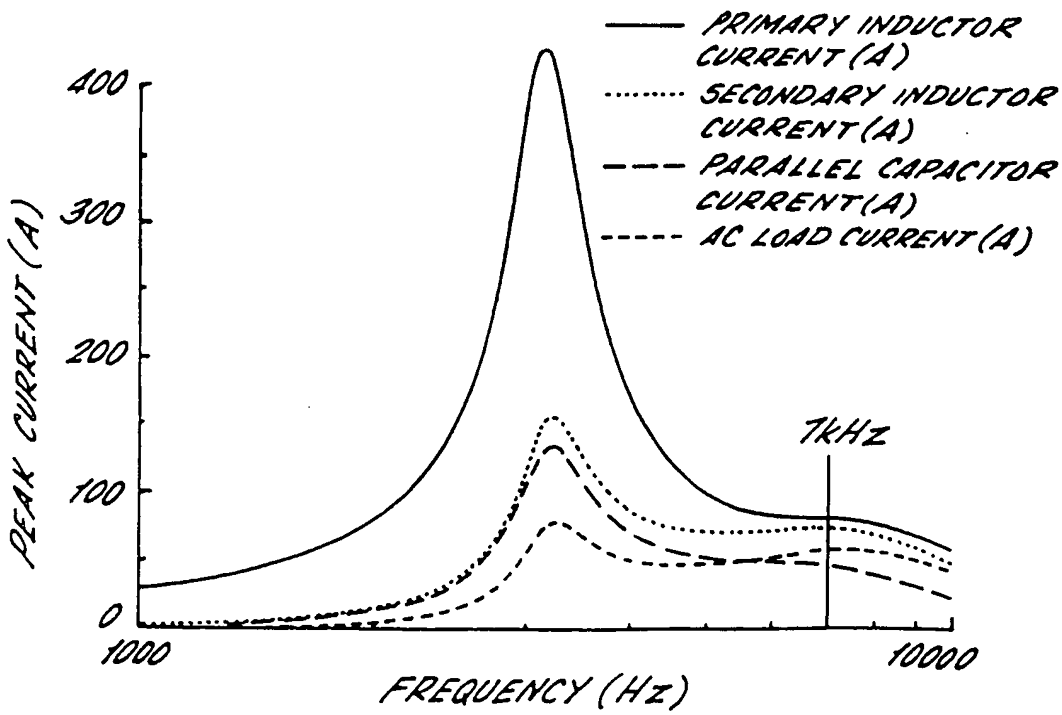


FIG. 6. FREQUENCY RESPONSE OF SYSTEM CURRENTS.



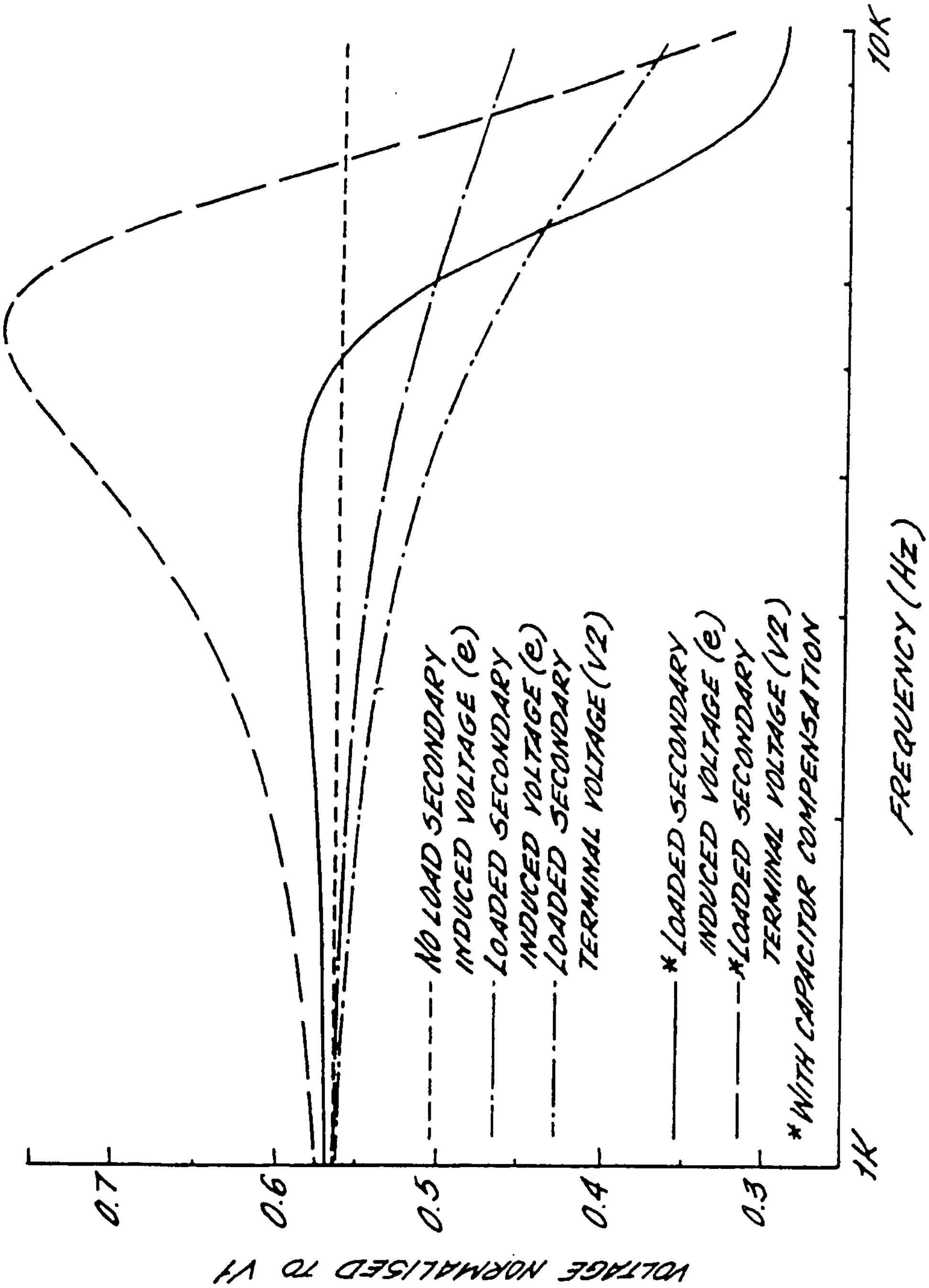

NO LOAD SECONDARY
INDUCED VOLTAGE (e)
LOADED SECONDARY
INDUCED VOLTAGE (e)
LOADED SECONDARY
TERMINAL VOLTAGE (V2)
*LOADED SECONDARY
INDUCED VOLTAGE (e)
*LOADED SECONDARY
TERMINAL VOLTAGE (V2)
*WITH CAPACITOR COMPENSATION
0.7
0.6
0.5
0.4
0.3
VOLTAGE NORMALISED TO V1
1K
10K
FREQUENCY (Hz)

FIG. 7.

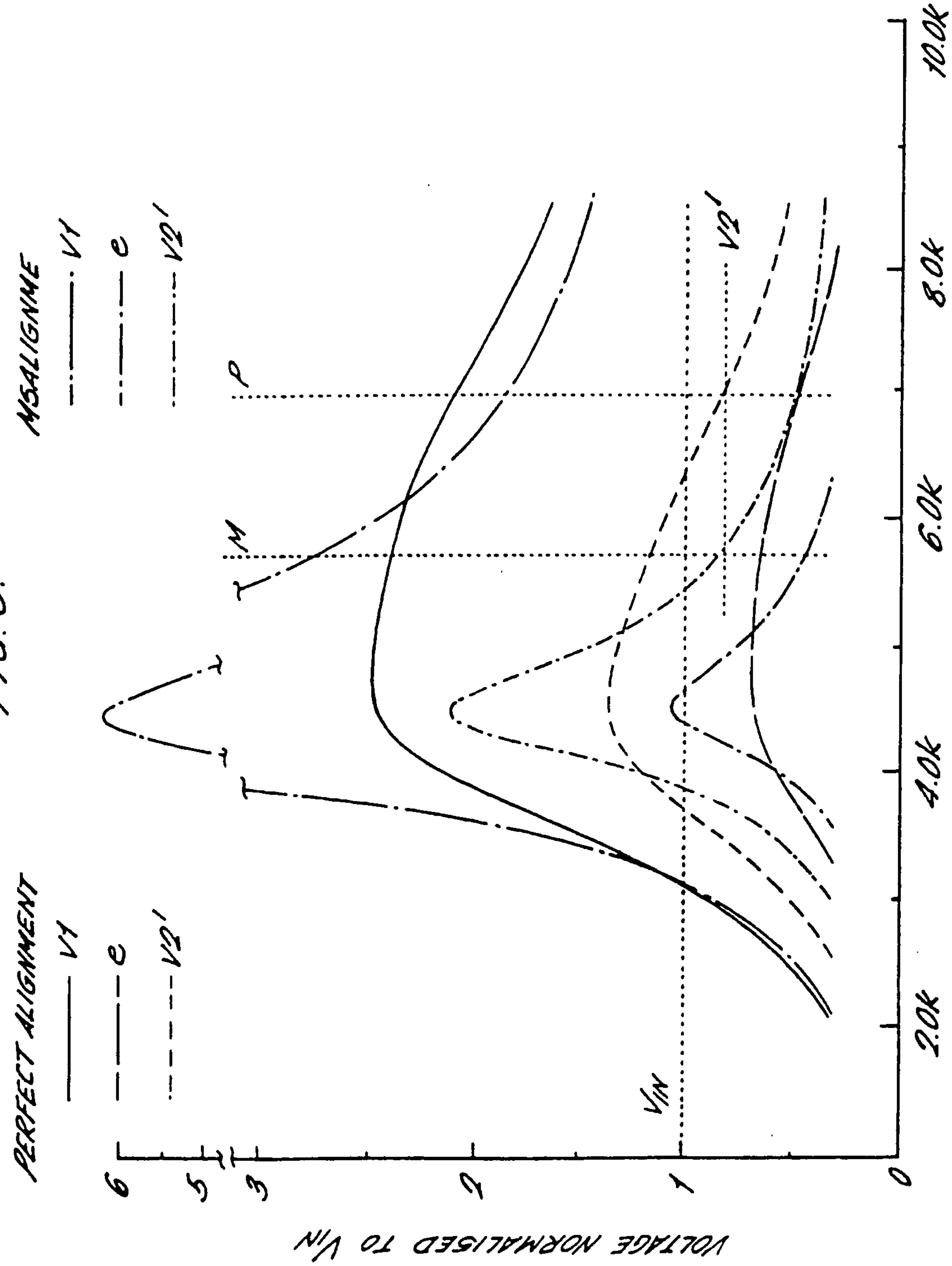

PERFECT ALIGNMENT
V1
e
V2'
MISALIGNME
V1
e
V2'
P
M
V2'
VIN
0
1
2
3
5
6
VOLTAGE NORMALISED TO VIN
2.0k
4.0k
6.0k
8.0k
10.0k

FIG. 8.

FIG. 9.

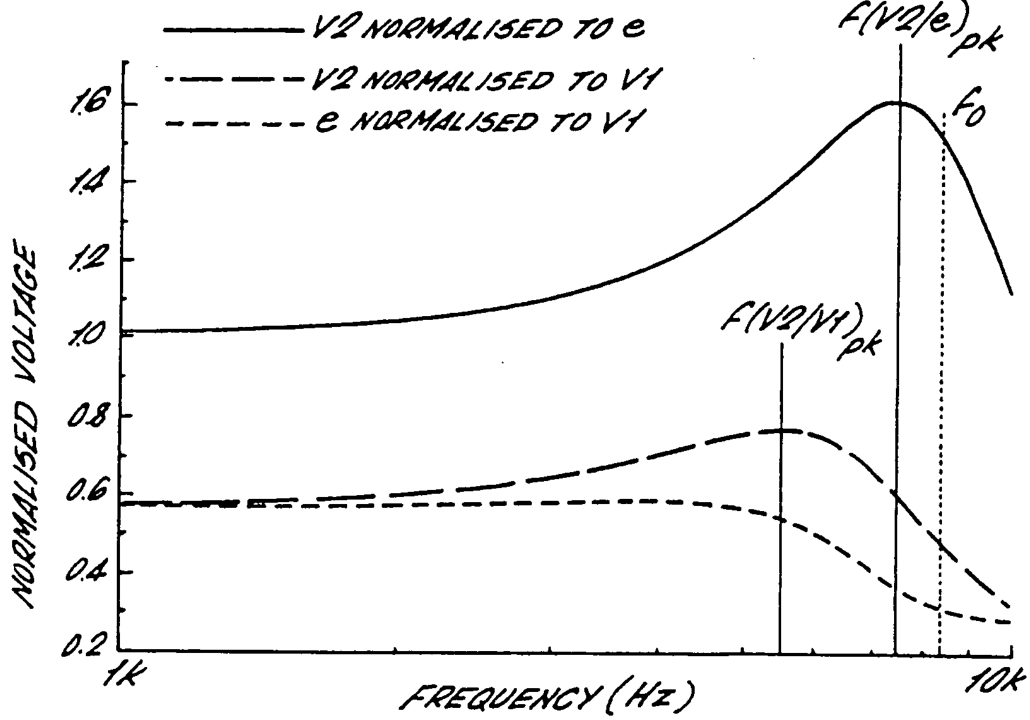
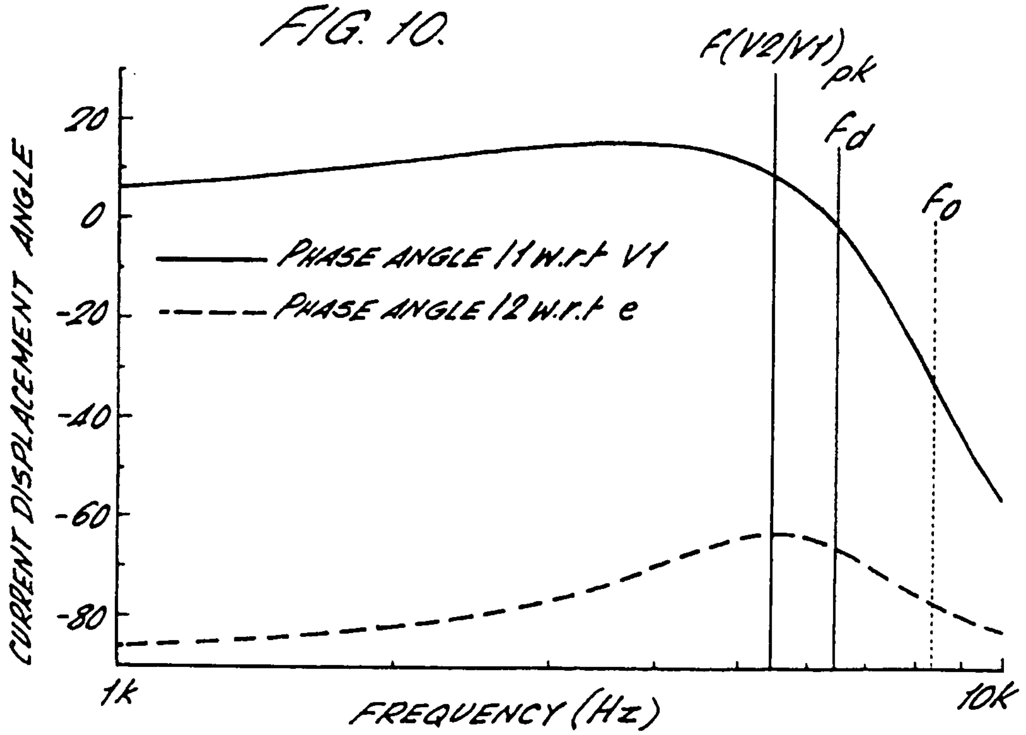

V2 NORMALISED TO e
V2 NORMALISED TO V1
e NORMALISED TO V1
F(V2/e)pk
F0
F(V2/V1)pk
NORMALISED VOLTAGE
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
1k
10k
FREQUENCY (Hz)

FIG. 10.


F(V2/V1)pk
Fd
F0
CURRENT DISPLACEMENT ANGLE
20
0
-20
-40
-60
-80
PHASE ANGLE I1 w.r.t V1
PHASE ANGLE I2 w.r.t e
1k
10k
FREQUENCY (Hz)

INTERNATIONAL SEARCH REPORT

Inte ional Application No
PCT/GB 00/00844

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H02J7/02 H02J5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H02J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 94 28560 A (ERA PATENTS LTD ;PEDDER DONALD AUSTIN GRANT (GB); SKINNER ANDREW J) 8 December 1994 (1994-12-08) cited in the application abstract ---	1-10
A	US 5 654 621 A (SEELIG ANTON) 5 August 1997 (1997-08-05) cited in the application abstract ---	1-10
A	DE 197 26 840 A (MATSUSHITA ELECTRIC WORKS LTD) 2 January 1998 (1998-01-02) column 3, line 40 - line 43 -----	1-10

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 May 2000	02/06/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Moyle, J

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 00/00844

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		WO 9410004 A	11-05-1994
		EP 0666805 A	16-08-1995
		JP 8502640 T	19-03-1996
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		CN 1171646 A	28-01-1998
		US 5949155 A	07-09-1999